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Black carbon and charcoal records of fire and human land use over the past 1300 years at the Tongguan Kiln archaeological site, China

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ABSTRACT

To examine fire patterns and landscape evolution in the Xiangjiang River Basin over the past 1300 years, high-resolution charcoal and black carbon (BC, char and soot) records from the Tongguan Kiln archaeological site of historical ceramic production have been analyzed in combination with robust Optically Stimulated Luminescence (OSL) and accelerator mass spectrometry radiocarbon (AMS^{14}C) dating, archaeological documents, and paleo-environmental proxies (i.e., magnetic susceptibility, total organic carbon, XRF-derived elemental data, etc.).

Throughout history, charcoal and BC have recorded changes in regional land use at the Tongguan Kiln site. Peaks in char and macro-charcoal contents indicate that local smoldering fire occurrences were typical with large amount of fuel used for kilns between 1300 and 1100 years B.P. under wet climate conditions. These peaks coincided with the size of the Tongguan Kiln archaeological site, which led to reduction of forest cover from nearby mountains and activated soil erosion. Subsequently, the frequency of fire activity declined to a very low level between 1100 and 600 years B.P., coupling with the decline of the Tongguan Kiln, and with a warm period in the study region. Over the past 600 years, with sharp growth in population, regional fires increased to an unprecedented scale for land reclamation for dry crop cultivation during a cold period, which in turn resulted in further environmental deterioration.

In summary, shifts of fire patterns in the study site over the past 1300 years have been closely related to (1) climate variation; (2) the mode of human land use; and (3) vegetation type and fuel combustion efficiency. There was an interactive, complex relationship between these factors in the Xiangjiang River Basin, and these results suggest that the intensity and pattern of human land use could have further impacts on fire patterns and landscape evolution in response to climatic change of the East Asian Monsoon, in the past as well as in the future.

1. Introduction

Fire plays a critical role in geochemical cycling of the biosphere and in atmospheric patterns (Bowman et al., 2009; J. Yang et al., 2014). Fire regimes are also largely modulated by the climate (Moritz et al., 2012) and human land use (Marlon et al., 2008). Historically, wildfires have not only occurred in response to climate variability, but also reflect long-term change in human land use (Marlon et al., 2013; Tan et al., 2015). Climate change influences vegetation availability and fuel moisture through changes in precipitation and soil hydrothermal conditions, and thus indirectly affects the evolution of human land use and culture (Conedera et al., 2009). Regional land use also affects the distribution of vegetation and biomass burning patterns over thousands of years (Tan et al., 2015). Many previous studies have shown that climate has an important influence on the occurrence of fires (Archibald et al., 2009; Van der Werf et al., 2008). In particular, regional fire occurrences have been intimately linked with abrupt climatic changes with similar pacing at different scales (Marlon et al., 2009). However, composite charcoal records from populated regions of Australia, Europe, North America, and Central and South America indicate that

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anthropogenic impacts have been the primary factor controlling fire regimes during the late Holocene (Flannigan et al., 2009; Marlon et al., 2008; Pechony and Shindell, 2010). In China, the application of fire in slash-and-burn methods for land use was especially widespread over the Loess Plateau, as indicated by a number of population and land-use histories spanning the past 3000 years (Archaeological Institute of CASS, 1991; Shi, 2001). To date, some paleoenvironmental and archaeological studies have suggested links between environmental and cultural changes in the study region (Munoz et al., 2010; Newby et al., 2005). A growing number of documents have recorded the influence of catastrophic climate events, such as droughts and flooding, on past human societies. However, most reports have focused on either cultural or climate changes, and most have focused on environments where human vulnerability to climate change is most controversial, such as in arid settings (e.g., the Loess Plateau). Because the relationship between humans and environmental change has largely been ignored, these effects may not be immediately evident and can easily be overlooked at present. The interactions between climate, vegetation, and fire regimes are complex, and can be difficult to disentangle under modern conditions when fire regimes are even more strongly influenced by human activities. Because there is no direct way to distinguish human-set fires from wildfires in the paleorecords, detailed understanding of the relationships between fires, human activity, and climate change during the Holocene remains limited (Hawthorne et al., 2017; Tan et al., 2015; Wang et al., 2012).

Fire was one of the earliest tools for humans to influence the evolution of natural ecosystems (Bowman et al., 2009). Charcoal can be used to reconstruct local fires, for example, whereas black carbon (BC) can be used to infer trends in broader-scale burning (Thevenon et al., 2010; Wang et al., 2013; Zhou et al., 2017). BC is typically defined as the highly condensed carbonaceous continuum that formed by the incomplete combustion of fossil fuels and vegetation fires (Goldberg, 1985). BC comprises two major categories: char/charcoal and soot/graphite particles (Seiler and Crutzen, 1980). Analyzing patterns of charcoal and BC may allow us to shrink the spatial and temporal gaps in reconstructions of fire history and enable new insights into the global carbon cycle (Tan et al., 2015). Therefore, we have employed high-resolution charcoal and BC records, integrated with detailed paleoenvironmental proxies and archaeological records available from the study region, to contribute to the understanding of the underlying processes between fire and human land-use practices in response to climate variability since the middle of the Tang Dynasty (in the past 1300 years).

The Dongting Lake Plain is located in the southern part of the lower reaches of the Xiangjiang River Basin. This region is densely populated, and most of the land has been cultivated for rice fields. The Tongguan Kiln archaeological site is known as the cradle of doucai porcelain and was historically associated with intensive ceramic production. Nearby clearing by means of deforestation provided supplies for ceramic production kilns around the study site (Yang and Zhong, 2001). Here, we focus on the Tongguan Kiln site to investigate the role of fire patterns in the Xiangjiang River Basin and its interactions with human activity to examine the drivers and consequences of fires in the past 1300 years.

2. Regional setting and the sampling site

The Shizhuping profile (SZP) (lat. 28°25.154′ N, long. 112°49.593′ E, elevation 24 m above sea level) in the south of the Dongting Lake Plain in the lower reaches of Xiangjiang River Basin is about 27 km north of Changsha City and is marginal to the Tongguan Kiln archaeological site (middle to late Tang Dynasty; Geology and Mineral Resources Bureau, 1989; Fig. 1). In this study, a typical dark–brown soil sequence covering the past 1300 years was selected based on field observations of color, texture and structure. The Profile is pedo-stratigraphically correlated to each other (Table 1). The soil horizons and the stratigraphic boundaries in the profile are well preserved and clearly identifiable. The cultural layer was identified between 260 and 290 cm, which corresponds to the Middle to Late Tang Dynasty (Fig. 2). The mean annual temperature and precipitation in the study area are 17.2 °C and 1395 mm, respectively, with 80% of precipitation occurring between April and August. There are 15 rivers and their tributaries across the study region, and flooding occurs mainly in May and September. The site is located in a subtropical humid monsoon region characterized by warm, humid springs and summers, and arid autumns and winters. Forest coverage is 57.1% in the study region, and these forests are dominated by *Cinnamomum camphora* (L.) Presl., with subtropical evergreen broad-leaf forests, evergreen and deciduous broad-leaf mixed forests, deciduous broad-leaf forests, and moss elfin forests (Tong et al., 2009). Rice (*Oryza sativa* L.) is noted for its high degree of adaptability to red soil, paddy soil, and various climatic conditions. The Tongguan Kilns are located at the foot of Lanhua hillside on the northern shore of Shizhu Lake beside the Xiangjiang River, covering 5 km^2 (Fig. 1). From the available evidence, > 3000 individual kilns have been recorded from the Tongguan archaeological site. It has been reported that the construction of kilns commenced in the early Tang Dynasty, declined at the end of Five Dynasties period, and reached its peak in export of porcelain during the middle and late Tang Dynasty (The Relics Group of the Municipal Bureau of Culture in Changsha, 1980; Fig. 1).

3. Sampling, stratigraphy, and chronology

An age–depth curve was established using OSL and AMS-^{14}C sediment dating and archaeological identification of cultural remains retrieved from the profiles (Archaeological Institute of CASS, 1991; Wang and Qu, 2007; Table 2). One ^{14}C AMS and three OSL dates from the SZP profile analyzed at the OSL and AMS-^{14}C Laboratory of Peking University, China (Table 2). Charcoal samples were used for AMS-^{14}C measurements. One AMS (^{14}C) date from the SZP profile was used for the age model after calibration using CALIB 7.01 (Stuiver et al., 1998). On the basis of this chronology, the profile covers the past 1300 years. The relationship between age and depth was expressed by a change-point model with the most linear interpolations possible that best fitted the calibration ranges (Fig. 3). The OSL dates are given in years B.P. and ^{14}C dates are given in cal. years B.P. Many pottery debris and macroscopic charcoal from the Middle to Late Tang Dynasty (cal. 1240–1160 years B.P.) were identified between 260 and 290 cm in the SZP profile (Fig. 2). These data were then combined with dates obtained from nearby archaeological sites to create a chronology for the study sites. The chronological framework established in the study site also correlates well with other dated profiles in the Xiangjiang River Basin (Guo et al., 2016; Mao et al., 2009, 2014).

4. Experimental methods

We created pedo-stratigraphic subdivisions based on detailed field observations of the color, texture, and structure of the sediment profile. In total, 99 samples were collected at intervals of 2 or 10 cm. Magnetic susceptibility (MS) was measured with a Bartington MS2 magnetic susceptibility meter (0.47/4.7 kHz; Bartington, Witney, UK). Grain-size distribution was analyzed with a Mastersizer-2000 laser particle size analyzer using the hydrometer method (0.02–2000 μm; Mastersizer, UK Lewis, 1984) after HCl (10%) pretreatment to eliminate secondary carbonate. Copper (Cu), manganese (Mn), phosphorus (P), rubidium (Rb) and strontium (Sr) contents were analyzed using a PW2403 X-ray fluorescence spectrometer (Philips, HOL). Total organic carbon (TOC) was analyzed using a Vario EL III elemental analyzer (CN mode; Elementar, Germany). A 30-g sample of sediment was processed for charcoal and pollen analysis using slides prepared for pollen analysis (Moore et al., 1991). After HCl (18%) and Na_2CO_3 (2%) pretreatment to eliminate the secondary carbonate and humic components, respectively. Exotic *Artemisia* grains were added to each sample for calculating

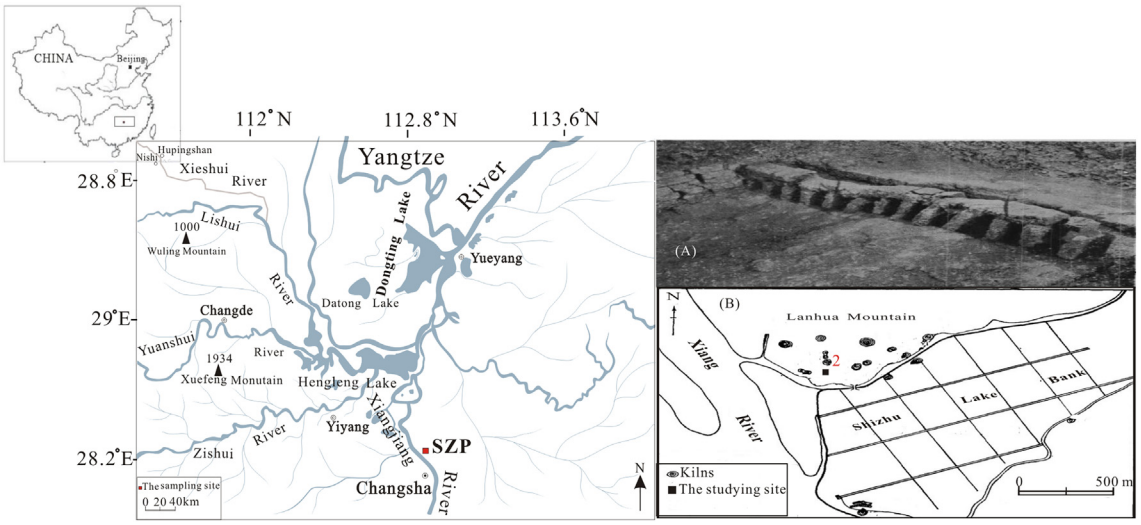

Fig. 1. Map showing the study site near the Tongguan Kiln archaeological site. The study site are marked as: the sampling profile at Shizhuping site (SZP); (A) showing the Kiln indicated by the arrow to number 2 (in red) in (B); (B) showing the location of Tongguan Kiln archaeological site (at the foot of Lanhua hillside on the northern shore of Shizhu Lake beside the Xiangjiang River). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
An description of the Shizhuping (SZP) profiles in the Xiangjiang river drainage basin of China.

Depth (cm)	Stratigraphic subdivision	Pedological description
70–0	Yellowish gray clay	Black patches and cutans, red piece, pale gray pebble gravel and abundant bio-pores; 5–10 cm, fragments of gray pottery
80–70	Yellowish gray clay	Abundant red iron-manganese cutans
145–80	Pale gray mud	Reddish yellow cutans, bio-pores
215–145	Silty clay	Pale yellow, no bedding
230–215	Yellowish gray clay	
260–230	Gray mud	Abundant pottery debris, charcoal
290–260	Cultural layer during the middle-late Tang dynasty	Abundant vat debris, burned soil
310–290		Yellowish gray, some soil burned, abundant charcoal, 5–10 cm thickness
?–310	Raw soil	Pale yellow

charcoal and pollen concentrations. The preparation of the Exotic Artemisia spore grains (the content of *Artemisia* spore: mean 10,000–12,000 grains·ml^{-1}) included: adding (*Artemisia*); adding the mixed solution $(CH_3CO)_2O$ and H_2SO_4 (9:1); decanting and washing and dyeing (Erdtman, 1969). Charcoal and pollen were extracted using a heavy liquid (1.8 g ml^{-1}) composed of HI, Zn, and KI (656 ml:145 g:644 g) (Liu, 1988). Three size groups were counted, < 50 μm, 50–100 μm, and > 100 μm, to allow discrimination between local fires and regional fires. Concentrations of BC, char, and soot were determined with a Model 2001 Thermal/Optical Carbon Analyzer (AtmAA Inc., Calabasas, CA) using the IMPROVE thermal/optical reflectance method after acid pretreatment (HCl 10% and HF 48%) to remove carbonates and the mineral fractions. For this process, mostly volatilized carbon evolves in a pure He atmosphere while the temperature is heated stepwise to 120, 250, 450 and 550 °C to produce the OC_1, OC_2, OC_3, and OC_4 thermal carbon fractions. Then, 2% O_2/98% He atmosphere is introduced after the OC_4 peak returns to baseline, and oxidized carbon evolves at 550, 700 and 800 °C to produce the EC_1, EC_2, and EC_3 fractions. The POC nearly evolves as part of the EC_1 fraction. Char and soot contents were calculated as described by Han et al. (2007, 2009): char = EC_1 − POC, soot = EC_2 + EC_3. OSL dating was carried out with a Riso-TL/OSL-DA15 Dating System using the fine-grain regeneration method in the TL/OSL and AMS-^{14}C dating laboratory at Peking University.

5. Results and interpretation

Total charcoal concentrations in this profile ranged between 22 and 2, 917 grains g^{-1}, with high charcoal concentrations (868–2917 grains g^{-1}) in the past 300 years, and lower charcoal concentrations (22–664 grains g^{-1}) between 11,00 and 600 years B.P. The concentration of fine charcoal particles (< 50 μm) varied between 22 and 2909 grains g^{-1}, and account for the dominant portion of total charcoal concentrations, which indicates that regional wildfire episodes dominated the study site. However, the concentration of coarse charcoal particles (> 50 μm) varied between 0 and 88 grains g^{-1}, which suggests that local wildfire events occurred frequently in the past 600 years at the study site (Fig. 4A, B).

In this study, char and soot concentrations varied from 0.04 to 6.12 mg g^{-1} and from 0.06 to 1.21 mg g^{-1}, respectively. Large amounts of char (0.20–6.12 mg g^{-1}), suggesting an increase in local to regional fire occurrences or in the amount of biomass burning, appeared during the interval 1300–1100 years B.P., whereas high soot concentrations (0.37–1.21 mg g^{-1}), suggesting an increase in regional fire occurrence and much broader-scale burning, appeared in the past 200 years. Low char (0.04–0.20 mg g^{-1}) and soot (0.08–0.20 mg g^{-1}) concentrations occurred in the interval of 1100 years B.P. to 200 years B.P., which are comparable to the charcoal records (Fig. 4C, D).

In this study, the char/soot fraction ratios varied from 0.28 and 35.7. High values of this ratio (3–35.7) were found between 1285 and 1100 years B.P., which suggests that local fires or local biomass burning occurred frequently during that period, whereas low values (0.28–3.0) appeared from 1100 years B.P. to the present (Fig. 4E).

At the SZP site, magnetic susceptibility values ranged from 4.93×10^{-8} to 90.60×10^{-8} m^3 kg^{-1}, and exhibited a "U-shaped" trend (Fig. 4F). Very high magnetic susceptibility values were observed for the lower part of the sediment profile, with peaks occurring between 1300 and 1100 years B.P. (88.20×10^{-8} m^3 kg^{-1}). Then, stable, constant lower values occurred between 1180 and 600 years B.P. ($4.93–20 \times 10^{-8}$ m^3 kg^{-1}), followed by a gradual rise over the past 600 years (90.60×10^{-8} m^3 kg^{-1}). The high values at the two ends of the sediment profile indicate intensified soil erosion, which may be associated with fire activity caused by human beings.

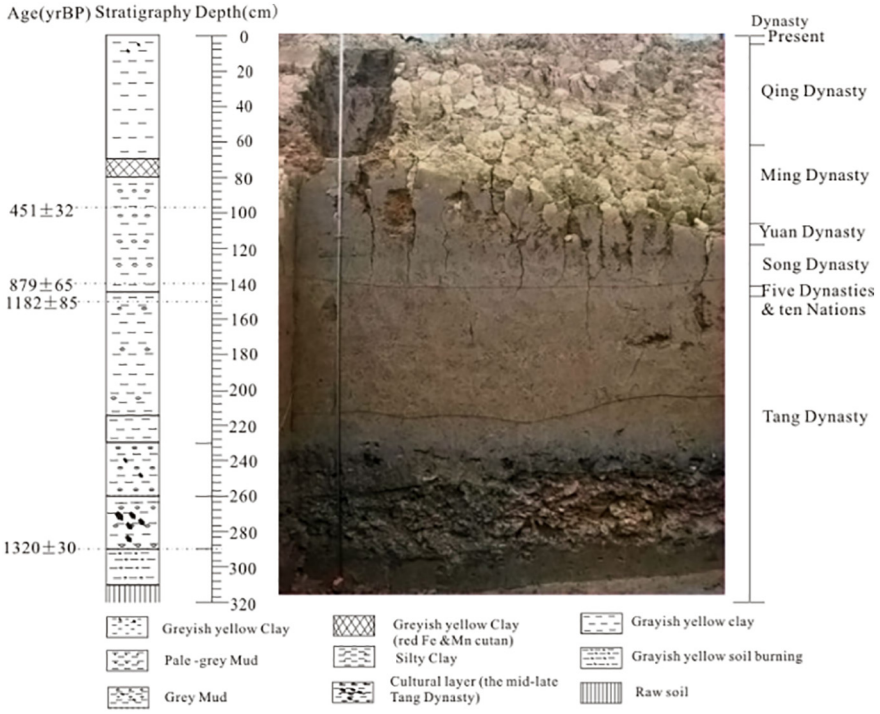

Fig. 2. Photographs of the Pedo-stratigraphic subdivision and chronology of profile from in the Tongguan Kiln archaeological site in the lower reaches of Xiangjiang river drainage basin.

TOC concentrations in this profile varied between 0.24 and 2.21 mg g^{-1}, whereas lower TOC values (0.24–0.63 mg g^{-1}) appeared from 1100 years B.P. to the present, which suggest low vegetation cover. Higher TOC values (0.66–2.21 mg g^{-1}) with several peaks were present between 1300 and 1100 years B.P., which indicate wetter conditions and dense vegetation growth during soil formation (Fig. 4G).

In the SZP profile, total Cu, Zr, and P content varied from 8 to 121 mg kg^{-1}, 211.40 to 314 mg kg^{-1}, and 632 to 3579 mg kg^{-1}, respectively, and showed similar trends to values of magnetic susceptibility (Fig. 4H, I, J). These elemental contents were normalized according to titanium content as a reference to avoid interference from grain size, sediment source, or mineral composition in the process of heavy metal sedimentation (Summers et al., 1996). The results suggest that both changes in soil erosion of the accumulated dust and the intensity of human land use practices occurred simultaneously.

In the SZP profile, the clay/silt fraction ratio varied between 10% and 15%. Low values of this ratio (10%–12%) occurred between 1270 and 1150 years B.P., which suggest a floodplain depositional environment and activated soil erosion, whereas high values of this ratio occurred from 1100 to 300 years B.P. (Fig. 4N).

In the SZP profile, pollen records indicate that the tree cover began to decrease from 80% to 25%, and a subsequent increase to a stable level of 40%, suggesting human beings have largely been responsible for the evolution of the mountain woodland ecological landscape over the past 300 years (Fig. 4P).

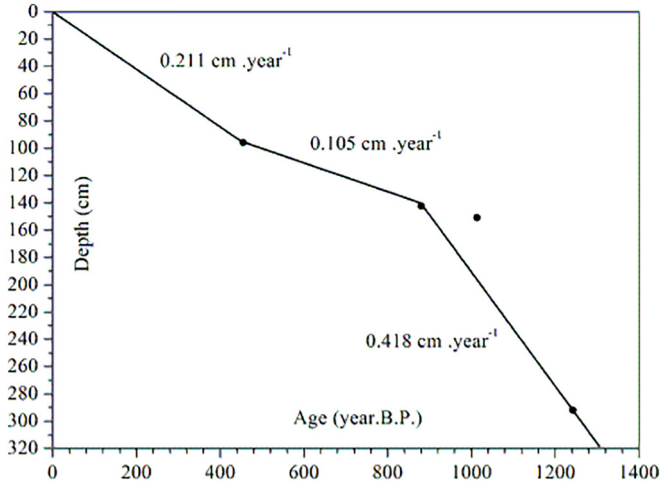

Fig. 3. The age/depth curve of the SZP profile in the lower reaches of Xiangjiang river drainage basin.

6. Discussion

Variations in charcoal concentration indicate the frequency and intensity of wildfire occurrences in the past (Whitlock and Larsen, 2001). A previous study (Huang et al., 2006) suggested that fine

Table 2
AMS^{14}C/OSL chronology data in SZP profile at the Tongguan Kiln site.

Lab number	Sample (depth)	AMS^{14}C/OSL date	2σ age interval	Age (years B.P.)
AB120171	SZP-01 94–96 cm	451 ± 32		451
AB120172	SZP-02 139–141 cm	879 ± 65		879
AB120173	SZP-03 149–151 cm	1182 ± 85		1182
BA120171	SZP-04 290–292 cm	1320 ± 30 (AMS^{14}C)	1170–1300 (cal. years B.P.)	1240 (cal. years B.P.)

Three OSL samples and one AMS^{14}C sample were measured at the AMS^{14}C/OSL (Calibrated with CALIB 7.01) Laboratory of the Peking University in China.

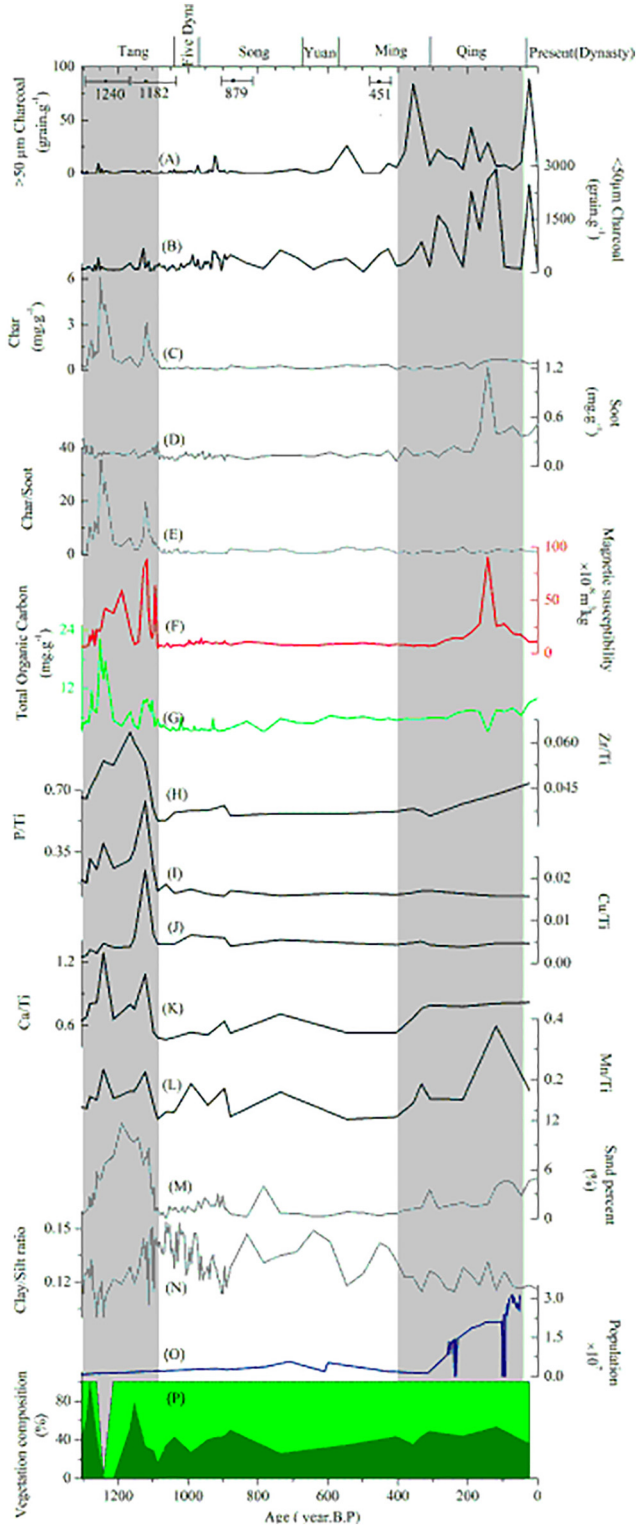

Fig. 4. Comparison of various proxies in the lower reaches of Xiangjiang River Drainage Basin with other records during the past 1300 years; (A) charcoal concentration (> 50 μm) at the SZP site; (B) charcoal concentration (< 50 μm) at the Shizhuping site (SZP); (C) char concentration values at the SZP site; (D) soot concentration values at the SZP site; (E) the ratio concentrations of char and soot at the SZP site; (F) low-frequency of magnetic susceptibility (MS) data at the SZP site; (G) the value of total organic carbon (TOC) data at the SZP site; (H) the ratio concentration data of Zr and Ti at the SZP site; (I) the ratio concentration data of P and Ti at the SZP site; (J) the ratio concentration data of Cu and Ti at the SZP site; (K) the ratio concentration data of Ca and Ti at the SZP site; (L) the ratio concentration data of Mn and Ti at the SZP site; (M) the percentage of component of sand at the SZP site; (N) the ratio component of clay and silt at the SZP site; (O) estimated population changes in Hunan province since 1300 years (He and Zhang, 1984); (P) the vegetation composition at the SZP site (light green indicates non Arboreal pollen percents of total grain; dark green indicates the pollen grains from Arboreal pollen percents) in the lower reaches of Xiangjiang River region over the past 1300 years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

charcoal particles (< 50 μm) indicate regional wildfire events, whereas coarse charcoal particles (> 50 μm) provide a record of localized wildfires. High-resolution BC (char and soot) records preserved in accretionary soil profiles have been used to reconstruct fire history and human activities in response to climate change (Han et al., 2012; Wang et al., 2005), whereas char and soot, based on their differences in size (with char particles being larger than soot at a submicron scale) (Han et al., 2010), have been used to reflect local to regional biomass burning and broader-scale burning (Han et al., 2016). The charcoal and BC records from the SZP profile show a pattern of low concentrations between 1100 and 600 years B.P. and high values between 1300 and 1100 years B.P. and during the past 600 years B.P. High charcoal and BC concentrations were present for the past 300 years. Over the last several hundred years, human-induced fires became an important factor in landscape evolution (Pechony and Shindell, 2010). This archaeological site provides an arena to integrate new data and generate new findings on how humans may not only cause but also respond to climate change, both in the past and in the future. In this section, we discuss the linkages between fire events and landscape variability recorded at the study site.

6.1. *Increased fire and soil erosion between 1300 and 1100 years B.P. (middle to late Tang Dynasty) associated with human kiln activities*

The paleo-climatic records between 1300 and 1100 years B.P. (ca. 700–900 CE, mid to late Tang Dynasty) suggest that the climate was warm and slightly wet with high variability in seasonal precipitation (He and Zhang, 1984; Yang and Zhong, 2001; Li et al., 2011; Chen et al., 2015). In addition, it is estimated that the average temperature was 1 °C higher than in the present, and that precipitation was characterized by a pattern of greater flooding in southern China because of the "warm period of the Sui and Tang Dynasties" (Ge et al., 2010, 2013a, 2013b). Increased effective moisture from atmospheric net energy transference led to frequent flood events and continuous heavy precipitation in local areas of the Xiangjiang River Basin (the study area) as a result of the increasing strength of the East Asian Monsoon (Yan et al., 2015). Pollen records indicate that tree cover began to decrease to 40%, and fell to below 20% between 1200 and 1100 years B.P. (Fig. 4P), and the vegetation cover was characterized by subtropical evergreen broad-leaved forest (Li et al., 2011). Peaks of higher macro-charcoal and char content (682 grains g^{-1} and 6.12 mg g^{-1}, respectively) indicate a clear increasing trend in local biomass burning between 1300 and 1100 years B.P. (Fig. 4A, C). At the SZP site, there are numerous archaeological kilns of the "dragon" style within a 5-km radius (Fig. 1; The Relics Group of the Municipal Bureau of Culture, 1980). Peaks of higher Cu and P contents (122.70 and 3579 mg kg^{-1}; Fig. 4I, J) were closely related to biomass burning for porcelain production (Cu and P contents of modern soil: 25.0 and 502 mg kg^{-1}; Environmental Monitoring Station of China, 1990). Previous study has indicated that the chemical components of ware glaze for porcelain from the Tongguan Kiln generally contain high concentrations of Cu, P, and iron as coloring reagents, all of which show that some wood ash may have been used as a raw material to make glazes in ancient China. Consequently, in the SZP profile, high

concentrations of Cu, P, and char in sediments are direct evidence of the large capacity for porcelain production and biomass burning from these kilns during the period (Zhang and Cuo, 1985). Thus, it can be surmised that local fires at that time can be attributed to excessive anthropogenic deforestation and fuel use for kilns, aside from natural wildfires under the warmer climate conditions, which likely resulted in slope instability at the study site and activated soil erosion. These conditions led to a trend of mountain flooding and mudslide occurrences in the study area between 1300 and 1100 years B.P. (ca. 700–900 CE, mid- to late Tang Dynasty).

Strikingly, our char and soot records show much greater char concentrations than soot concentrations during this period, which demonstrates that local fires dominated at that time. This finding is in good agreement with the archaeological evidence of kiln activities during this period (The Relics Group of the Municipal Bureau of Culture, 1980). In addition, the greater amounts of char than soot found in these warm and slightly wet conditions are also consistent with the fact that smoldering fires, rather than burning fires, tend to occur in those conditions (Han et al., 2016). In contrast to the records of regional biomass burning (Fig. 4A, B, C, D), the char peaks are clearly much higher than those of the micro- and macro-charcoal at the SZP site, whereas macro-charcoal still showed lower values of peaks, which suggest differences in fuel combustion efficiency and fuel characteristics (Han et al., 2016; Tan et al., 2015; Thevenon et al., 2010). This difference was attributed to the large quantities of forest woods used as fuel and raw materials for the kilns, and the tendency to favor smoldering fires with high ignition temperatures, which easily yielded much more char than charcoal.

Additionally, clear peaks of char content and the char/soot ratio occurred in the intervals of 1300–1200 years B.P. and 1200–1100 years B.P., which are consistent with when ceramics at the Tongguan Kiln developed from imitation porcelain during the early to mid-Tang Dynasty to the doucai porcelain decoration style during mid- to late Tang Dynasty, as represented by the changing copper oxide contents (CuO) of the ware glaze of the porcelain (Fig. 4J).

Historical documents reveal that a large number of people were forced to migrate southward from the Yellow River Basin to the Xiangjiang River Basin 1300–1200 years B.P. because of the An Lushan Rebellion (Zhou, 1997). With advanced ceramics techniques, some craftsmen also migrated to this area and engaged in kilning. Many kilns were located in the low-lying lands of the Tongguan site near Shizhu Lake at the beginning of Tang Dynasty and developed rapidly. A vivid description of the Tongguan Kiln area was discovered in a poem entitled “Shizhu”, by the eminent poet Li Tingyu (808–862 CE).

“Applying clay to make marvelous porcelain,
Clearing large numbers of forests for fuel use of kilning.
As the burning flames tint the river red,
The smoke blends into the clouds over Dongting Lake”

The poem depicts a vivid scene of the Tongguan kilns, which is now acknowledged by archeologists as the home of the doucai porcelain decoration style. In 1998, a shipwreck found in the South China Sea called “Black Stone” contained nearly 67,000 pieces of porcelain from the Tongguan Kiln, dating back to the Tang Dynasty (826 CE). It is evident that a large capacity for porcelain production can be traced to this period.

In addition, the presence of detrital inputs (indicated by Zr concentrations, Fig. 4H) and the clear increase in magnetic susceptibility ($88.2 \times 10^{-8}\,m^3\,kg^{-1}$, Fig. 4F) toward a period when erosional events were mainly controlled by soil erosion processes on the slope, and likely resulted from the addition of erosion-derived materials (char and charcoal) from excessive anthropogenic deforestation associated with burning for fuel for the kilns during that period (Fig. 4). Historical documents show that the flooding frequency was once at 18 years interval and the water level was 1 m higher than in the present (Zhang et al., 2014; Liu, 1998). The ratio of clay to silt and the sand composition suggest that the sand component increased considerably, whereas the clay and silt components declined considerably during this period (Fig. 4M, N). These records suggest that there was a significant increase in the effects of overland flow and soil erosion processes on the slope that coincided with the mountain flood season in the study region. Ceramic production resulted in deforestation, and the acceleration of soil and water loss subsequently brought about torrential flooding. Many of the kilns at the SZP site were vulnerable to severe soil degradation and destruction from floods (Hunan Forest Editorial Board, 1989), which was indicated by the transposition of deposits of various sizes of charcoal and BC associated with flooding around the area. This finding was confirmed by a 30-cm-thick layer of gray mud mingled with particles of charcoal found between 230 and 260 cm from 1160 to 1100 years B.P. (ca. 840–900 CE, the Late Tang Dynasty) in the SZP profile. Therefore, the regional environment has been subjected to devastation since 1300 years B.P. Regionally, charcoal records from several profiles from the Chinese Loess Plateau have shown that biomass burning for clearing land for cereal cultivation decreased to a relatively low level when dry farming was gradually established on the Loess Plateau starting about 1500 years B.P., despite the drier climate during that period (Huang et al., 2006; Tan et al., 2013, 2015). In the study area, the interval of 1300–1100 years B.P. was characterized by local smoldering fires largely associated with fuel use for kilning under warm climate conditions. Therefore, the spatially and temporally heterogeneous patterns show that fire activity has been closely related to changes in human production modes and fuel combustion efficiency over the past 2000 years (Han et al., 2016; Tan et al., 2013, 2015).

6.2. *Regional low fire activity between 1100 and 600 years B.P. (Song and Yuan Dynasties) with a slightly dry climate*

The paleo-climatic records between 1100 and 600 years B.P. (ca 900–1400 CE, Song and Yuan Dynasties) suggest that the climate was warmer and slightly drier than that of the Sui and Tang Dynasties, which may correspond to the “Medieval Warm Period” during the Holocene (Tan et al., 2011; Li et al., 2011; B. Yang et al., 2014; Chen et al., 2015). Historical documents show that the flooding frequency was once at 5 years interval during that period (Liu, 1998). Compared with the warm period of the Sui and Tang Dynasties, flood frequency increased significantly because of high variability in seasonal precipitation from the more intense East Asian Monsoon (Ge et al., 2010, 2013a, 2013b; Yan et al., 2015). Lower macro/micro-charcoal and BC contents show that regional biomass burning decreased sharply during this period (Fig. 4A, B, C, D). Cu and P contents and magnetic susceptibility also dropped to low values (Fig. 4I, J). Historical documents suggest that the Tongguan Kiln was in decline during this period (The Relics Group of MBCC, 1980), which resulted in less deforestation to fuel kilns and lower amounts of biomass burning at the study site with increased warm conditions.

Although pollen records show that tree cover still remained at about 40% and mountain forest appeared to decline at elevations near the study site and non-tree cover increased to at 60% or so (Fig. 4P), the landscape around the lake was covered in hygrophytic herbs and shrubs during those periods (Li et al., 2011). The ratio of clay to silt and the sand composition suggest that the clay and silt components declined to 12%, and the sand component increased moderately during this period (Fig. 4M, N), which corresponds to the warmer and drier climate. Deceasing tree vegetation cover (Fig. 4P) and weak soil development between 1100 and 800 years B.P. likely resulted in a general trend of susceptibility to torrential flooding and soil erosion activation as a consequence of long-term excessive deforestation (Liu, 1998). The evidence suggests that many of the kilns near the study site on the low-lying plains by Shizhu Lake may have been frequently submerged by flooding over a long period between 1100 and 800 years B.P. (Song Dynasty, Yan et al., 2015), which was confirmed by a layer of silty clay between 230 and 145 cm in the SZP profile (Fig. 2).

Based on comparison of our findings with those of other studies (Carcaillet et al., 2009; Hope et al., 2009; Marlon et al., 2012; Nelson et al., 2006; Vannière et al., 2008), we have found that the lower occurrence of regional fire events at the study site was attributed to the combined effects of relatively humid climate conditions and less human activity between 1100 and 600 years B.P.

6.3. Regional high fire frequency and environmental deterioration during the past 600 years because of agricultural activities and cold climate

The paleo-climatic records in the past 600 years B.P. (ca. 1400 CE, Ming and Qing Dynasty), together with lower MS and lower TOC contents, suggest that the climate has become cooler with weak biopedogenesis over the past 600 years in the study of region, which may correspond to the "Little Ice Age" (1300–1900 CE, He and Zhang, 1984; Yang and Zhong, 2001; Li et al., 2011; Chen et al., 2015).Historical documents show that the flooding frequency was approximately once at four years interval, most of which occurred in the coldest phase of the "Little Ice Age" (300–100 years B.P., Zhu et al., 1997).

Pollen records indicate that the tree cover began to decrease from 40% to 30%, and a subsequent decrease in the stable level indicates that human beings have largely been responsible for the evolution of the mountain woodland ecological landscape over the past 300 years (Fig. 4P). Peaks of higher amounts and concentrations of macro/micro-charcoal (42 grains g^{-1} and 2909 mg g^{-1}, respectively) indicate a clear increasing trend in regional biomass burning (Fig. 4A, B). In addition, peaks of high contents of Mn and Ca in the SZP profile (2, 327.9 mg kg^{-1} and 5.%, Fig. 4K, L) were closely related to biomass burning for dry crop cultivation (contents of Mn and Ca in modern soil: 389.7 mg kg^{-1} and 3.25%; Environmental Monitoring Station of China, 1990). Historical documents show that the population increased from northern China and was associated with intensive land reclamation for cultivation across the region (He and Zhang, 1984). Thus, it can be surmised that regional fires at that time under more cold climate condition can be attributed to excessive anthropogenic forest clearance by human-set regional fires for cultivation in the past 300 years (Yang and Zhong, 2001).

Strikingly, in contrast to the records of regional biomass burning (Fig. 4A, B, C, D), peaks of micro- and macro-charcoal are clearly much higher than those of char at the SZP site during this period. This difference was caused by intensive burning of large quantities of shrubs and herbs for dry crop cultivation, which tend to favor flaming fires with low ignition temperatures, and easily yielded much more charcoal than char in the depositional site, as recorded by high charcoal and low BC contents in the past 300 year. Higher soot contents show that there was a clear trend toward aridity in the Xiangjiang River Basin in the latest Holocene, which may correspond to climatic "deterioration events" associated with the "Little Ice Age" (1300–1900 CE; Chen et al., 2015; Tan et al., 2011; Wu and Liu, 2004).

Historical documents show that the population increased by a factor of almost 11 at the study site until the Qing Dynasty, mostly because of migration from northern China (He and Zhang, 1984). As a consequence of the sharp growth in population since the end of Qianlong era during the Qing Dynasty, biomass burning associated with land reclamation for the cultivation of corn and sweet potatoes increased greatly (He and Zhang, 1984; Yang and Zhong, 2001). This reclamation reached an unprecedented scale of intensive biomass burning for dry crop cultivation across the region when the climate became more arid, and also accelerated runoff and erosion–redeposition processes on the slope in the study region, and the degradation of the primitive mountain forest landscapes, as inferred from the higher MS values ($10.76–90.6 \times 10^{-8}$ m^3 kg^{-1}) and low ratios of clay to silt (the sand component increased, whereas the clay component decreased; Fig. 4M, N). Meanwhile, ecological degradation risk also increased around the study site during this period (Yang and Zhong, 2001). However, the extremely high concentration of micro-charcoal in the topsoil layer at the SZP site may have resulted from the burning of rice stalks in the fields after harvests in recent years, when villagers replace coal with these stalks for cooking and heating. This finding suggests that land reclamation for farming began to drive landscape succession through the ignition of fires at the study site during the past 300 years.

Specifically, the variation of fire patterns over time appears to be marked by emission of various carbonaceous particulate materials (charcoal, char, and soot) because of differences in fuel combustion efficiency, and also reflects the evolution of the mode of production in response to climate variability (Marlon et al., 2013; Tan et al., 2015).

7. Conclusions

Throughout history, charcoal and BC have recorded changes in regional land use at the Tongguan Kiln site Collapse scenarios associated with large-scale deforestation to fuel kilns between 1300 and 1100 years B.P. (ca. 700–900 CE, middle to late Tang Dynasty) and large-scale land reclamation for dry crop cultivation at the study site over the past 600 years (Ming and Qing Dynasties) were the result of mountain forest reduction, activated soil erosion, and environmental deterioration (flooding and water saturation), which in turn, ultimately limited long-term human development in this region.

In short, fire patterns mainly depended not only on rapid climate events, but also on vegetation type, fuel combustion efficiency, and regional heterogeneity in human land use and ignition sources in the Xiangjiang River Basin over the past 1300 years. The close association between millennial-scale variations in fire and human practices in the Xiangjiang River Basin shows that human land use may represent the most important driving factor on fire patterns and landscape evolution in response to climatic changes of the East Asian Monsoon in the past and in the future.

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